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THE RELATIONSHIP BETWEEN COMPUTER-AIDED ACQUISITION AND LOGISTICS SUPPORT (CALS) AND CONCURRENT ENGINEERING

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The Institute for Defense Analyses Paper P-2306, The Relationship Between Computer-Aided Acquisition and Logistics Support (CALS) and Concurrent Engineering, presents an analysis of the relationship between the CALS program and concurrent engineering. The paper is limited to the two principal relationships between CALS and concurrent engineering: multi-enterprise information frameworks and individual information exchange standards. The approach was to survey relevant CALS and concurrent engineering literature, including the data and workshop publications used in preparing the IDA Report R-338, The Role of Concurrent Engineering in Weapons System Acquisition. The CALS information was derived from MIL-HDBK-59, interviews with the CALS Director, two CALS conferences, and interviews with two DoD industry representatives to the Industry CALS/Concurrent Engineering Steering Group. Conclusions and recommendations are presented.

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Preface

IDA Paper P-2306, *The Relationship between CALS and Concurrent Engineering*, documents the results of an analysis requested by the DoD CALS Policy Office. The purpose of this analysis was to identify the high-level view of the relationship between the CALS and Concurrent Engineering programs.

The importance of this document is based on partially fulfilling the objective of Task Order T-B5-602, Concurrent Engineering, which is to investigate the conduct of Concurrent Engineering in a Computer-aided Acquisition and Logisitic Support (CALS) environment. P-2306 will be used to identify future CALS development activities and is directed towards the DoD CALS Policy office staff who will make decisions on CALS and Concurrent Engineering programs.

The document was reviewed on October 4, 1989 by the members of the following IDA Computer & Software Engineering Division Peer review: Mr. William Akin, Dr. James Pennell and Dr. Robert Rolfe.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1 PURPOSE

The purpose of this paper is to report on the findings of the study of the relationships between CALS and Concurrent Engineering and to recommend to the CALS Policy office how best to support concurrent engineering. It is intended to satisfy paragraph 4.d of IDA Task order T-B5-602, amendment 5.

1.2 SCOPE

The scope of this paper is limited by the level of effort established at the initiation of the project. As a result, not all relationships between CALS and Concurrent Engineering have been explored. This study is limited to a high-level view of the two principle relationships between CALS and Concurrent Engineering, namely multi-enterprise information frameworks and individual information exchange standards.

1.3 APPROACH

The approach to preparing this paper was to survey relevant CALS and concurrent engineering literature, including the data and workshops used in preparing the IDA Report, R-338, *The Role of Concurrent Engineering in Weapons System Acquisition* [WIN88] which contains the definition of Concurrent Engineering used here. The CALS information was derived from MIL-HDBK-59, interviews with the CALS Director, two CALS conferences, and interviews with two DoD industry representatives to the Industry CALS/Concurrent Engineering Steering Group.

1.4 BACKGROUND

The Department of Defense is addressing the serious issues of how to increase the quality and decrease the cost and schedule of its weapon systems developments. CALS and Concurrent Engineering address these issues at different levels.

Major weapons systems now typically require ten to fifteen years to develop and deploy. To successfully develop effective weapons systems and to remain competitive in the global market, the time to develop major weapons systems must be substantially reduced. Concurrent engineering is an approach to decreasing costs, increasing quality, and decreasing schedule by improving the engineering process. The Undersecretary of

Defense (Acquisition) issued a policy memorandum on March 9, 1989 that stated DoD's intent to encourage the use of Concurrent Engineering in system developments (See Appendix A). This intent has been reinforced by the current USD(A) and the current Deputy Secretary of Defense.

Updating and maintaining system documentation has become a significant issue in its own right, requiring an inordinate amount of manpower and expense simply to maintain and distribute. For example, the onboard documentation for some ships now weighs as much as fifty-five tons. The CALS Policy office is moving both government and industry data management practice toward compatibility with electronic publishing systems and making it possible for the government to accept deliveries of weapons system documentation in digital form. Future CALS plans aim to integrate this digital data.

1.4.1 CALS PHASES I & II

From the Foreward of the CALS military handbook, MIL-HDBK-59 [CAL88, iii]: "The purpose of CALS is to improve industry and DoD productivity and quality, and thus improve supportability, military readiness, and combat effectiveness . . . .

The objectives of CALS are

a. to accelerate the integration of design tools . . . such as those for reliability and maintainability into contractor computer-aided design and engineering systems as part of a systematic approach that simultaneously addresses the product and its life cycle manufacturing and support requirements.

b. to encourage and accelerate the automation and integration of contractor processes for generating weapon system technical data in digital form.

c. to rapidly increase DoD's capabilities to receive, store, distribute, and use weapon system technical data in digital form to improve life cycle maintenance, training, and spare parts reprocurement, and other support processes."

These objectives were formulated in 1985 and were included in the CALS military handbook when it was published in 1988. The relative importance of the objectives have changed. Objective "a", the acceleration of design tool integration is now a part of the Concurrent Engineering effort and a less emphasized effort of CALS. Objective "b" now has a higher priority within the CALS program.

These objectives were further refined in an August 5, 1988 memorandum by Deputy Secretary of Defense William H. Taft, IV. That memorandum set forth three specific requirements of all new weapon systems entering development after September 1988:

- integration of contractor information systems and processes
- government access to that information
- delivery in digital form

The CALS effort is divided into two phases as described in the *CALS Program Implementation Guide* [CAL88, iii-iv]. Near-term (Phase I) goals include ". . . attainment of increased levels of interfaced, or integrated functional capabilities, and specification of requirements for limited government access to contractor data bases, or for delivery of technical data to the government in digital form." Long-term goals (Phase II) include " . . . integration of industry and DoD data bases . . . . The technology to accomplish this will be incrementally developed and proven." The first phase includes the intent to evolve from current paper deliverables to digital deliverables and the second phase is intended to integrate the data together.

1.4.2 CONCURRENT ENGINEERING

The classic engineering life cycle has four major phases which are performed serially. The life cycle begins with a requirements phase in which the reason for the product is explored, the major issues are surfaced, and its interfaces into other systems are defined. Next is a product development phase during which the product is designed. The design process normally takes into account many tradeoffs. A process development phase takes the design of the product and determines how that product will be economically and reliably manufactured. Finally a prototype phase undertakes an actual build of the product to verify all the previous steps. This engineering cycle then feeds into a manufacturing cycle which may include redesign because of the realities of full-scale production.

The serial life cycle has been in use for quite some time, but its shortcomings have become apparent in today's more competitive commercial markets and in a Department of Defense environment in which costs and schedules are increasing beyond realistic budgeting and military expectations. A well-known problem with this life cycle model is that errors in analysis of requirements are often only discovered during the prototype phase, by which time much of the funds allocated for research and development have been consumed. While the prototype validates all the previous phases of the life cycle, little can usually be done to remedy a poor analysis, product design, or process. Even when funds to reaccomplish earlier phases of the life cycle have not been expended, the time to discover errors is lengthy and is a major obstacle to shortening the product realization schedule. Finally, little will be known about the performance and producibility characteristics and less will be known about the reliability until after a prototype has been built. The problems with this life cycle are serious and must be addressed as they are starting to be addressed by the notion of concurrent engineering.

Concurrent engineering is an attempt to integrate the somewhat independent phases of the classic serial life cycle and reorienting the design process toward ensuring the efficiency of downstream processes. Specifically, the design of the processes by which a product is to be manufactured and supported must be integrated as part of the design of the product.

The IDA Report [WIN88, 11] defines concurrent engineering as " . . . a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements."

Ideally, decisions about the design are optimally placed within the life cycle, but the life cycle does not become truly concurrent. The word "concurrent" applies to the integration of engineering considerations, not to the life cycle itself. The phases of the concurrent engineering life cycle differ from the conventional sequential phases, but retain their feed-forward character. They also, however, incorporate feedback of information from the downstream activities of manufacturing and support into the upstream conceptualization, requirement, and design phases. Concurrent engineering is not an engineering discipline in the usual sense but affects the management activities that go into supporting a product during the entire life cycle.[1]

Concurrent engineering, as defined, above is a proven product and process engineering approach. It causes simultaneous unit and life-cycle cost reductions, quality improvement, and schedule reduction. Concurrent engineering succeeds because it integrates related activities and focusses then on making sure that the designed product can flow through the downstream processes of manufacture, support, and operation efficiently even in the face of uncontrollable factors. When practiced at a world-class[2] level, concurrent engineering integrates and focusses on robustness in manufacture, support, and use for the purposes of reducing cost and schedule and increasing user perceptions of quality.

The integration of effort in concurrent engineering is over disciplines (e.g., computer hardware, software, reliability, thermal, mechanical) and over functions (e.g., maintenance, marketing, manufacturing, design). The integration of effort implies a

1. In particular, concurrent engineering is *not* "concurrency" of design and production, and idea commonly confused with concurrent engineering.

2. The details of how concurrent engineering is practiced at a world-class level can be found in [CLA89].

different information flow from that in a sequential, fractionated process.

With respect to the information flow in concurrent engineering, Goranson defines four possible interpretations of the IDA concurrent engineering definition [GOR]. The first is concurrent engineering as management and engineering tools to facilitate team approaches. The second is concurrent engineering as communications technologies and standards to expand the reach of development teams. The third is concurrent engineering as data and modeling techniques to allow integrated information bases. The fourth is concurrent engineering as fully concurrent, independent simultaneous operations on distributed master-indexed information. These interpretations span short through long-term approaches with corresponding risks and payoffs.

Thus, concurrent engineering seeks to improve the engineering process by functional and disciplinary integration of the engineering process. It includes a focus on engineering quality products by engineering quality processes and an emphasis on continuous improvement of these processes. Various levels of information integration may be used within such an engineering approach.

1.5 OVERVIEW

Concurrent engineering can be thought of as the integration of engineering effort while CALS is the integration of engineering information. There are two areas of explicit, shared interest between the two initiatives. These are multi-enterprise information frameworks and individual information exchange standards, discussed in sections 2.1 and 2.2. Conclusions and recommendations for further action are found in section 3. The Works Consulted section lists all of the documents used in this study. Appendix A contains a copy of the Taft memo which partially defines the CALS program. An article on concurrent engineering is reprinted in Appendix B.

1.6 ACRONYMS

CALS	Computer-aided Acquisition Logistics Support
DoD	Department of Defense
EDIF	Electronic Design Interchange Format
FMECA	Failure Modes Effect Criticality Analysis
FRACAS	Failure Reporting, Analysis, and Corrective System
IGES	Initial Graphics Exchange Standard
NIST	National Institute for Standards and Technology
OPSEC	Operational Security
PDES	Product Data Exchange Specification
QFD	Quality Function Deployment
R&M	Reliability & Maintainability
SPC	Statistical Process Control
VHDL	Very High Speed Integrated Circuit (VHSIC) Hardware Description Language

2. MULTI-ENTERPRISE INFORMATION FRAMEWORKS

The CALS program is concerned with the data transfer aspects of weapons systems developments while the concurrent engineering initiative seeks to change the whole life cycle approach. An effective view of this relationship has already been adopted by the CALS Policy office: CALS is an enabling or facilitating initiative for several areas of process improvement, one of which is concurrent engineering. The obvious relationship is that the CALS acceleration of information distribution and delivery will materially enhance the efficiency of concurrent engineering processes. Some users of concurrent engineering feel that other aspects are more fundamental to cost, schedule, and quality of the products, in particular, those having to do with a management approach. The size and complexity of DoD system developments, however, indicate a need for vastly improved communication and sharing of design information. In fact, every successful application of concurrent engineering described in the IDA Report includes attention to information integration [WIN88, Appendix A].

An information framework is a set of standards and specifications for managing engineering information. This information framework sets forth ". . . a structure for establishing, storing, executing, and evolving information-based policies and tools" [WIN88, 142].

An information framework is analogous to a household electric drill where engineering tools are analogous to the drill bits. Great economies are produced by standardizing on a few common drill bit shaft sizes. No one would consider buying a drill or drill bit which was nonstandard because the economies gained by restricting drill bit shaft sizes is obvious, but many of our defense software projects use custom information and engineering tools and are built to custom specifications. Performance requirements are often cited as an argument to substitute a custom for a standard tool.

The successful evolution of an object-oriented information framework is the central issue of CALS Phase II and, in particular, of advanced stages of the PDES, Inc., effort. The CALS Phase I effort is aimed at standardizing engineering data into a digital form, but without necessarily imparting sufficient semantics to that data to permit engineering analysis to be feasible. The CALS Phase II effort attempts to put all the data into one logical place, but the question then becomes, "How is all this data to be interpreted?"

A carefully evolved information framework is necessary to avoid several technological risks. These risks include the stagnation of information technology through the use of inappropriate or outdated standards, the acquisition of weapons system data without acquisition of critical information relationships, and the construction of incompatible high-performance information tools.

The information framework then must attempt to avoid these risks by becoming:

a. adaptable to each installation (i.e., that it can accommodate and support the particular tools, engineering functions, and policies of each organization).

b. distributed (i.e., that it can execute on multiple [heterogeneous] hosts to maximize performance and availability, can take advantage of the distribution of resources and functions in a network, and will allow control over resources).

c. portable (i.e., that it will provide the common functions in different hardware/software environments without re-implementation).

d. extensible (i.e., that it can accommodate new tools, new types of engineering information, and new hardware and software technologies).

e. evolutionary (i.e., that it can accommodate the technology changes in a smooth progression without interrupting users or incurring major re-integration costs). [LIN86A, 3-33]

Developing multi-enterprise information frameworks without an understanding of information models or architectures creates a condition where the technology will stop evolving. This implies a requirement on the CALS program to develop a common understanding of engineering semantics, and to manage the evolution of the standards. These standards should be expected to continue to evolve as new technologies develop.

The CALS program is well-placed to be the central organization to be focussed on the development of multi-enterprise information frameworks. CALS appears to be taking on this role. The success of concurrent engineering will be influenced by the attainment of the previously listed information framework goals by the CALS Policy office.

The direction that the CALS program is moving can be described by defining two dimensions of the program: integration of data and semantic content of data (See Figure 1). Each dimension has two states. The first dimension, integration of data, maps the phases of the CALS program as it moves from the goal of defining standard data exchange formats to the more ambitious goal of integration of databases. The second dimension, semantic content of data, shows the transition of information from the syntax only to the syntax and semantics orientation. The semantic information is important because it is the semantic information which will make analysis of the data feasible. For example, an engineering drawing of a circle within a rectangle is potentially ambiguous: it isn't possible without additional semantic information to decide whether the wire-frame diagram represents a circular hole within a solid rectangular surface or a solid circular shaft within a rectangular space (See Figure 2).

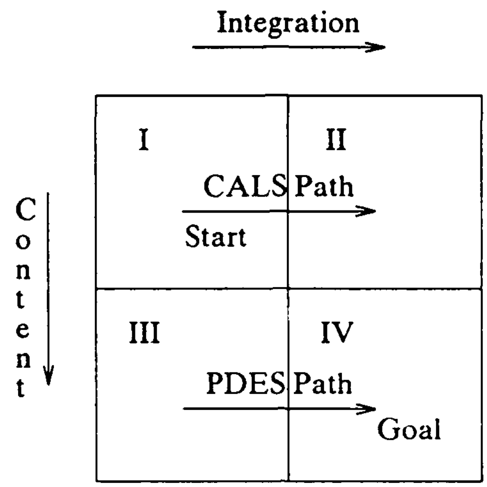

Figure 1. Two Dimensions of the CALS Program

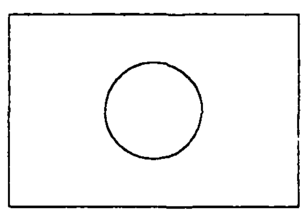

Figure 2. Circular Hole or Solid Shaft?

The intersection of the dimensions' states produces four sectors as depicted in Figure 1. Sector I represents the state of having standard exchange formats for syntax-only data, which the CALS Phase I program is now accomplishing. For the purposes of this discussion, it is our starting point and for CALS was a reasonable first target. Sector II represents the state of the CALS Phase II effort (when it is achieved), where data has been amassed and is accessible remotely, and is accessible through logical interfaces. Sector III represents the situation where the data has well-defined internal relationships and semantics, but is not yet integrated. Sector IV represents the state reached when the integrated database (regardless of how implemented) contains information sufficiently complete that it can be interpreted by a person or automated tool at a later date with no access to the author.

In order to bootstrap the integration of digital information the strategy of CALS Phase I has concentrated on information exchange standards, clearly a prerequisite to information integration.

The mainstream CALS program is moving from Sector I to Sector II, but also needs to make the transition to Sector IV. The path to Sector IV can be made from Sector I via Sector II or it could also be made via Sector III. Currently, the CALS program's direction is to evolve from Sector I, to II, and then to IV. Changing the path to include work in Sector III would allow some work in the semantic arena so that results are available when required. The CALS Policy Office has stated that data exchange with semantics is an objective of PDES, Inc.

Another fundamental question related to information frameworks arises: is this information framework required for the purposes of CALS of the same kind as that desirable for concurrent engineering? This may or may not be independent of the similarly phrased question about the information required for the two activities. For purposes of this discussion an extreme version of CALS objectives is assumed: information is to be amassed to allow the government to reprocure parts, subsystems, or systems with minimum (ideally, no) reverse engineering. This is fundamentally different from the concurrent engineering objective of making the product realization and support process more efficient in that it focusses on one event in the support process. It is beyond the scope of this study to detail this issue, but it is known that there are differences of opinion on it and it is a topic worthy of discussion in the CALS and CE technical communities.

2.1 INFORMATION EXCHANGE STANDARDS

Given the desire for an information framework, there is the separate issue of the specific information exchange standards required for the smooth execution of the engineering process. Examples of such standards are Very High Speed Integrated Circuit

(VHSIC) Hardware Description Language (VHDL), Electronic Design Interchange Format (EDIF), and Initial Graphics Exchange Standard (IGES).

CALS Phase I has standardized the delivery of images to the government in raster form. This is a valuable advancement over the current method of delivering microforms. But for future activities, the CALS program has recognized that standardizing at the raster level is limiting.

Standardizing images at the raster level accomplishes a worthy goal, that future copies of the images can be produced remotely upon demand and that paper copies don't need to be maintained. But that misses the promise of collecting large masses of data in the first place: the promise that, once data is acquired, automatic processes can manipulate and analyze it. For example, if all the engineering data for constructing a building is stored in a database, then an automated process should be able to analyze the data for conformance to building standards. All kinds of questions could be automatically answered that would otherwise have to be determined by a manual, error-prone process. For instance, "Does the building have enough electrical outlets to meet the building code?", and "Is the structure strong enough to house heavy industrial equipment?"

In the same way, the database representing an aircraft could permit automated processes to deduce answers to questions like "What is the mean time between failure for the flight control system?", "What is the performance envelope predicted for this aircraft?", "What is the maximum g-force the aircraft can safely undergo when fully fueled?", ". . . when fuel is nearly empty?", "What is the current parts availability for exchanging the rear stabilizer?" "If the cargo bay area were stretched three feet what else would have to change to maintain center-of-gravity?" These questions can be answered through a process of analysis, not just through a process of experimentation. From a concurrent engineering point of view, it is desirable that more of the process of analysis will occur during the design stage, rather than after a prototype is built. By the time a prototype is built, changes are difficult and expensive to implement. The scheduling of major design decisions when their downstream impacts can be assessed is central to the concept of concurrent engineering and to the consequent production of robust products.

The *Report of the CALS Reliability & Maintainability (R&M) Summer Study on Complex Electronics* [MDS89, A-1—A-26] lists several R&M functional capabilities which represent opportunities for integration. See Figure 3 for some of the automated processes that should be able to make use of an extensive weapons system database.

Reliability and Maintainability Allocation
R&M Operational Impact Analysis
R&M Lessons Learned Data Base
Serial Reliability Prediction
System Level Reliability Prediction
Parts List Verification
Electrical Stress Analysis
General Design Rule Checking
Stress/Fatigue Analysis
Simulation—Digital
Simulation—Analog
Sneak Circuit Analysis
R&M Model Generators
Failure Modes Effect Criticality Analysis (FMECA)
R&M Sensitivity Analysis
Maintainability Prediction
Solid Modeling—Equipment Remove/Replace Analysis
System Level Solid Modeling Accessibility Assessment
Redundant/Fault Tolerant Design Evaluation
Testability Analysis
Testability Fault Isolation Coverage Analysis
Generation of Test Vectors
System Level Testability Fault Isolation Coverage Analysis
Packaging Density Estimation
Design Decision Traceability
Producibility Design Analysis
Environmental Control and Sensitivity Analysis
First-Cut Reliability Estimator
Automatic Parts Placement for Thermal Effects Considerations
Basic Reliability Design Guides
Reliability Related Shock and Vibration Stress Analysis
Parts Tolerance Analysis (Design Sensitivity)
Automated Parts Application Review
Failure Reporting, Analysis, and Corrective Action System (FRACAS)
Cooling Effectiveness for Reliability and Power Estimating
Nuclear Hardening Analysis
Transient Analysis

Figure 3. R & M Processes

These are only a few of the many processes or analysis tools which should be able to make use of the weapons system database. Development of these analysis tools would, however, be impeded without the semantic information that is called for in the above information framework requirements. The semantic information in a weapons system database generally cannot be collected or deduced after the fact and must be "designed for" and collected well before any analysis is to begin. A side issue which must be resolved is how the semantic data can effectively be put into the PDES database.

Some electronics design vendors have demonstrated the beginnings of such an integrated information framework for electronic circuit design. Using these systems an engineer can specify a schematic for an electronic circuit and perform various integrated analyses to determine whether physical placement of components will result in violations of minimum clearances between boards or between components, whether heat from operation of the components will result in temperatures that are unacceptably high or lead to unacceptable reliability estimates, and whether vibration modes exist which may lead to system failure. These analyses were accomplished in the past through physical prototyping or through separate analyses systems. While both of these previous alternatives were fairly slow, with the integrated analysis systems now in use, designs can be interactively tested and tuned for reliability, resulting in quick design turnaround.

Using these analysis tools will change the way designers and managers think about their designs. Many managers manage what they can most easily measure. Since product reliability, maintainability, survivability, simplicity of manufacture, etc. are more difficult and take more time to measure than the usual performance measures of speed, size, weight, power and functionality, those difficult-to-define qualities often are not effectively managed. One of the benefits of automating the analysis of a design for these more abstract measures of performance will be a greater understanding of their role in the product life cycle. Furthermore, concurrent engineering requires that these analyses be done in concert with rather than in parallel with the product design. Therefore, an *efficient* exchange of design and analysis information between engineering disciplines is required. This, in turn, implies well thought-out neutral exchange standards that minimize information loss.

Of all the different classes of information useful for concurrent engineering and that could be standardized, and beyond those already in a standardization process it is not yet clear which are of enough common interest to be considered for standardization. However, Statistical Process Control (SPC) is already of sufficient interest to warrant SPC information representation standardization efforts. Quality Function Deployment (QFD) may become widely enough used to warrant the same consideration.

In discussions at the recent DoD/NIST Workshop on Statistics and Quality Methods participants agreed that there are variations in meaning among Statistical

Process Control charts that are not obvious from looking at the charts. Differences in semantics among popular variations need to be standardized, otherwise the information is likely to be misleading. The Electronic Industry Association (EIA) is proposing SPC standards which might be suitable as a future CALS standard [EIA89B, EIA89C].

The government might consider promoting QFD or a similar method as a way of tracking systems engineering information. If that happens, the executing team should start considering information exchange formats in the early stages, thus creating a defacto proposed standard and avoiding a great deal of useless effort spent in developing QFD tools around differing but equivalent information representations. Such tools are already available and information exchange among them is impossible.

Not enough information is available now to determine which other classes of information are of sufficient interest to warrant such a standard, but progress could be made toward determining which are. The information representations should be specific enough to be unambiguous, but not so specific as to overconstrain contractor processes.

2.2 INFORMATION SECURITY

One further issue of common interest to the CALS program and within concurrent engineering were described by several people interviewed during this study and is appropriate to mention here. Essentially the problem is one of information sharing versus information security. Putting detailed information about how to produce and maintain a weapon system into electronic form carries new security risks. These concerns arise from the unprecedented access now possible through electronic information systems. The CALS Policy office is working this issue through the Industry Steering Group.

3. CONCLUSIONS AND RECOMMENDATIONS

1. Standardized semantic information in the CALS weapons system database is important and needs to be included in the development of weapons system database standards, so that design analysis can be accomplished economically.

2. The evolution of object-oriented multi-enterprise information frameworks is an important factor in the success of the CALS and Concurrent Engineering programs.

3. SPC information is a good candidate for a standardization effort.

4. The massive integration of weapons system design and producibility data creates new security risks which must be addressed. It is therefore appropriate that CALS continues to pursue this issue.

5. A plan needs to be developed to get all the data associated with manufacture into the PDES database. This data needs to include the entire end-to-end manufacturing process.

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APPENDIX A

TAFT MEMO

THE DEPUTY SECRETARY OF DEFENSE

WASHINGTON, D.C. 20301

5 AUG 1988

MEMORANDUM FOR SECRETARIES OF THE MILITARY DEPARTMENTS
DIRECTOR, DEFENSE LOGISTICS AGENCY

SUBJECT: Computer-aided Acquisition and Logistic Support (CALS)

To achieve productivity and quality improvements, my September 1985 letter on CALS set the goal of acquiring technical data in digital form (rather than paper) for weapon systems entering production in 1990 and beyond. We have now taken a major step toward routine contractual implementation. The Department of Defense (DoD) has coordinated with industry the first in a series of CALS issuances of national and international standards for digital data delivery and access. These standards have been published in MIL-STD-1840A, "Automated Interchange of Technical Information," and supporting military specifications. The CALS standards will enable either digital data delivery or government access to contractor-maintained technical data bases.

Effective immediately, plans for new weapon systems and related major equipment items should include use of the CALS standards. Specifically:

- For systems now in full-scale development or production, program managers shall review specific opportunities for cost savings or quality improvements that could result from changing weapon system paper deliverables to digital delivery or access using the CALS standards.

- For systems entering development after September 1988, acquisition plans, solicitations, and related documents should require specific schedule and cost proposals for: (1) integration of contractor technical information systems and processes, (2) authorized government access to contractor data bases, and (3) delivery of technical information in digital form. These proposals shall be given significant weight for their cost and quality implications in source selection decisions. The CALS standards shall be applied for digital data deliverables.

DoD components shall program for automated systems to receive, store, distribute, and use digital weapon system technical information, including achieving the earliest possible date for digital input to DoD engineering data repositories. These systems shall be configured or adapted to support the CALS standards. Plans for CALS implementation and productivity improvements will be addressed in Defense Acquisition Board and Major Automated Information System Review Council acquisition reviews, and in corresponding Service and Agency reviews.

Each application decision shall be made on its own merits with respect to the productivity and quality improvements expected at either prime contractor or subcontractor level. The Under Secretary (Acquisition) will issue further guidance on contract requirements, such as CALS options, in invitations for bid; opportunities and safeguards for small business and other vendors and subcontractors; government and contractor incentives; and funding mechanisms for productivity-enhancing investments in automation and CALS integration by defense contractors.

I believe that CALS is one of the most important and far reaching acquisition improvements we have undertaken. I would appreciate having the Assistant Secretary (Production and Logistics) receive your plan of action within 90 days, including identification of systems where opportunities exist for cost savings or quality improvement through application of CALS technology, the investment required to achieve these benefits, and proposed schedules for implementation.

William H. Taft IV

William H. Taft, IV

cc: Under Secretary of Defense (Acquisition)
Assistant Secretaries of Defense

APPENDIX B

CONCURRENT ENGINEERING ARTICLE

Concurrent Engineering: Practices and Prospects

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ABSTRACT

This paper summarizes a 1988 investigation of concurrent engineering and its role in weapons system acquisition. Concurrent engineering has recently been promoted in the automotive, computer and electronics, and aerospace industries as a response to competitive pressures. Viewed as a more systematic approach to creating high quality products and bringing them to market at lower cost and in significantly less time, it also attracted the attention of the Department of Defense. In 1988, the Institute for Defense Analyses (IDA) was asked to investigate concurrent engineering and to identify any advantages that could be expected from applying it to weapons system acquisition.

We describe the investigation, present highlights of the evidence, and set forth the principal findings and recommendations. This paper includes the definition of concurrent engineering developed during the study. We offer a sample of reported benefits that include 60 percent reduction in product development time, elimination of two thirds of the inspectors in one factory, and several million dollars annual savings in chemical and soldering processes. We outline the methods and technologies of concurrent engineering—the process management ideas, the computer support, and the problem-solving techniques. We provide a conceptual framework to describe the continuing research needed in this area.

1. INTRODUCTION

The President's Blue Ribbon Commission on Defense Management (The Packard Commission) noted that weapons systems take too long to develop, cost too much to produce, and often do not perform as promised or expected.[3] Similar problems in automobile and electronics industries resulted in a crippling loss of market share by United States producers to offshore competition. Surviving companies in affected

2. *The work reported in this article was conducted as part of the Institute for Defense Analyses Project T-B5-602 under Contract No. MDA 903 84 C 0031 for the Department of Defense and first appeared in IDA Report R-338, "The Role of Concurrent Engineering in Weapons System Acquisition." The publication of this paper does not indicate endorsement by the Department of Defense or the Institute for Defense Analyses, nor should the contents be construed as reflecting the official positions of those organizations.*

3. *A Quest For Excellence*, Final Report to the President by the President's Blue Ribbon Commission on Defense Management, June 1986, p. xxii.

industries responded to competitive pressures by modifying their management, engineering, production, and customer support processes. Many of the modifications included a more systematic method of concurrently designing both the product and the downstream processes for producing and supporting it. This systematic approach is the fundamental theme of *concurrent engineering*.

In 1988, IDA, at the direction of the Undersecretary of Defense for Acquisition, examined concurrent engineering and presented recommendations to the Department of Defense. Our recommendations, along with findings of independent groups, helped to point out the need for new guidance concerning acquisition. On March 9, 1989, Dr. Costello, Under Secretary of Defense (Acquisition), provided interim program acquisition guidance for the Secretaries of the Military Departments and their Service Acquisition Executives concerning concurrent engineering and its role in the acquisition process. The interim guidance builds on existing DoD policy to articulate a top level approach to integrating the engineering processes that support DoD acquisition.

2. APPROACH

In response to initial reports from several companies, the Under Secretary of Defense for Acquisition (USD(A)) directed that the Institute for Defense Analyses (IDA) investigate concurrent engineering and its possible application to weapons system acquisition. An IDA study team was formed and the team, in coordination with representatives[4] from industry, academia, and government, collected information about concurrent engineering. The information gathering consisted of literature reviews, site visits, and workshops. The IDA study team followed the progress of another group that presented insights from a cross section of industrial officials regarding concurrent engineering, particularly senior management's perception of barriers and incentives to implementation. [Davi88]

A report of the initial IDA investigation was provided to the Department of Defense in December 1988. [Winn88] The report describes concurrent engineering in terms of success stories. It includes case studies of companies that simultaneously improved quality, decreased cost, and reduced development time through the application of concurrent engineering.

3. DEFINITION

Participants at the first IDA concurrent engineering workshop discussed concurrent engineering as it is practiced in several U.S. companies and developed the following definition to describe the practice.

> Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including

4. The authors acknowledge the contribution of individuals from the following companies: Aerojet Ordnance, Allied Signal, AT&T, Boeing, John Deere, Ford, Grumman, Hewlett-Packard, Honeywell, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments. We are also grateful for the contributions of members of the faculties of Carnegie Mellon University, MIT, University of Wisconsin-Madison, Princeton, University of Chicago, Brigham Young University, Harvard Business School, New Jersey Institute of Technology, Auburn University, and Rensselaer Polytechnic Institute. Scientists and engineers from Charles Stark Draper Laboratories, The National Science Foundation, The National Center for Manufacturing Sciences, the American Supplier Institute, the American Statistical Association, the National Institute for Standards and Technology, and many government scientists and managers also helped. Although the contributions of the many participants has been substantial, the names of their institutions should not be construed as an endorsement of this paper or its contents.

quality, cost, schedule, and user requirements.

Concurrent engineering is characterized by a focus on the customer's requirements and priorities, a conviction that quality is the result of improving a process, and a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise.

The integrated, concurrent design of the product and processes is the key to concurrent engineering. Figure 1 compares a sequential approach to product development, as shown at the top of the figure, with a concurrent approach in the lower half. In the sequential method, information flows are intended to be in one direction, from left to right as shown by the arrows. In the concurrent approach, information flows are bi-directional and decisions are based on consideration of downstream as well as upstream inputs. The companies studied in this report found that achieving this sharing of information required both organizational and technological change.

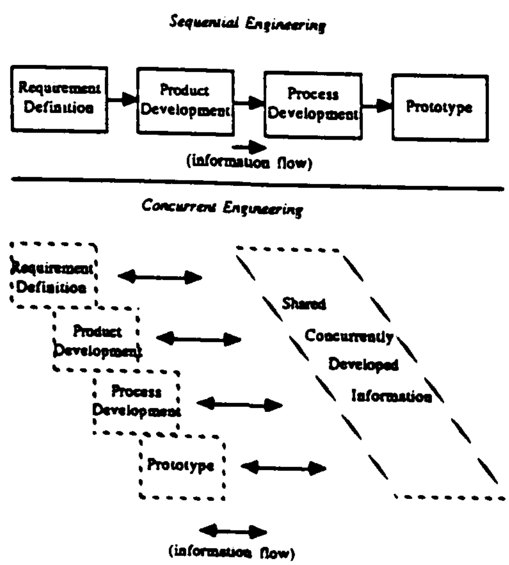

Figure 1. A Comparison of Sequential and Concurrent Engineering

The philosophy of concurrent engineering is not new. The terms "system engineering, "simultaneous engineering, and "producibility engineering have been used to describe similar approaches. In fact, a number of authors have described similar techniques and hundreds of companies have applied them successfully. [Haye88] Nevertheless, many companies have *not* adopted concurrent engineering because of the "fundamental, wrenching, far-reaching transformations that are required throughout the enterprise.[5]

Where changes were made, concern for *survival* in the face of increased competition (particularly from Japanese manufacturers) often provided the necessary incentive for companies to improve the quality of their products and increase the efficiency of their product development processes. As the pressure to improve quality and efficiency increased, newly developed computer-based design and analysis tools gave specialists from different engineering disciplines the freedom of working with the same description of the design to evaluate the effects of particular design features. The companies that have been successful in concurrent engineering have embraced the philosophy of continuing improvement, and they are using new tools as well as traditional techniques to implement this business philosophy.

Although the study team found examples of companies that are moving in the direction of concurrent engineering, it found no company claiming to have developed "the one best way. The people affected by the changes say that progress has been difficult, that mistakes have

5. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), p. 344.

been made, and that enthusiastic advocacy and support by top management have been essential. None of the companies said that concurrent engineering, in isolation, is capable of producing the type of improvements needed to remain competitive. Concurrent engineering is part of an integrated corporate competitiveness plan that emphasizes concepts such as those described by Deming[Demi86]. Nevertheless, they are pleased with their accomplishments and they are actively looking for additional improvements.

4. METHODS AND TECHNIQUES

The study team identified three complementary classes of activities that support concurrent engineering:

- engineering process initiatives such as the formation of multidisciplinary teams;
- computer-based support initiatives such as improvement of computer-based design tools, including giving the user an environment that integrates separately developed software; and
- use of formal methods including application of special purpose tools for design and production support.

Engineering process initiatives are management actions to improve the organization and the procedures used to develop a product. Involvement of representatives of manufacturing early in the design process is a minimal step in this direction. Most case studies show that companies form teams which include marketing, production, engineering, support, purchasing, and other specialists.[6] Team members are selected for their ability to contribute to the design effort by early identification of potential problems and by timely initiation of actions to avoid bottlenecks. The ability to work effectively as a member of a team is critical. Using multidisciplinary teams is not equivalent to forming committees where members often delay decision making; instead design teams get faster action through early identification and solution of problems.

Leadership at the highest corporate and government levels driving continuous quality and productivity improvement is a prerequisite for the success of the changes associated with these initiatives. Changes to the status quo, especially the cultural changes required for concurrent engineering, are not likely to be successful or to endure without top management leadership and support.

Most of the companies visited during this study have also undertaken substantial education efforts in team skills and related problem solving techniques.[7] Other management initiatives include the following:

- emphasizing attention to customer needs and quality improvement,
- improving horizontal integration of the organization,
- promoting employee involvement in generating new ideas for improvement,
- requiring engineering comparisons of proposed products and

6. Where companies form long-term partnerships with their principal suppliers, they often include representatives of the suppliers on the design team beginning with the conceptual design.

7. Boeing, Deere, IBM, ITT, McDonnell Douglas, Northrop, and Texas Instruments. Sources of education include local colleges and universities, special purpose institutes, consultants, and in-house education programs.

competitive offerings, and

- establishing closer relationships with suppliers to include supplier involvement during conceptual design phase.

Computer-based support initiatives cover a range of computer-aided tools, database systems, special purpose computer systems that improve design verification, and computer-based support of product design, production planning, and production. The companies differ in the sophistication of their systems, but those companies making advances in this area share a goal of using a single data object as a source for many engineering functions including design synthesis and verification as well as planning production processes. This use of a shared, common data object by specialists throughout an enterprise provides a mechanism for concurrently performing the product and process design tasks. Feature-based design and group technology are approaches to creating order and imposing regularity on the databases that support the design process.

A solid model of the object being designed is frequently used as the single data object that allows automated systems to be integrated. [Wolf87] Sometimes, several companies participating in a development team share access to the same computer representation of a solid model. Mechanical design, tooling, machining, and assembly need accurate solid models.

Computer tools that evaluate the behavior of potential designs are used extensively. Among companies doing electronic design, simulation is a critical tool. Aircraft companies use finite element models (FEM) and computational fluid dynamics (CFD) to support design.

Computer tools not only assist in the validation of proposed designs, they can also be used in synthesizing the design itself. Rule-based systems are sometimes used in design synthesis. In attempting to provide rule-based design systems, several companies[8] are developing practical applications of expert systems.

Formal methods[9] are difficult to categorize. They include techniques that date to the 1930s and more recent approaches. Statistical process control (SPC)[10], design of experiments, design-for-assembly (developed by Boothroyd Dewhurst Inc. [Dewh85]), value engineering and quality function deployment (QFD) are just a few of the formal methods discussed during the study.

In this group we include computer-based statistical tools for data analysis in support of both SPC and design of experiment. We also consider fundamental engineering philosophies such as the robust engineering principles as proposed by Taguchi to belong in this class. Quality function deployment (QFD), and the techniques used by Pugh are likewise seen as formal methods.

8. Litton Amecom, McDonnell Douglas Astronautics, Deere, IBM, AT&T, Texas Instrument, ITT, Northrop, and Hughes all mentioned some initiative in expert system or rule-based design.
9. See [Winn 88] Appendix B for further discussion of the formal methods.
10. Statistical process control is sometimes considered to be applicable only to manufacturing processes and not to design or service activities. There is abundant evidence that SPC provides direct benefits for improving a wide range of processes and that it provides indirect benefits to the design process when it is used in manufacturing. The indirect benefits result from feedback of more reliable information about manufacturing process capabilities and limitations. This information is used to design products with characteristics that match a company's ability to produce them.

[Pugh81]
Other methods that have been useful in problem solving include Ishikawa's [Ishi85] seven tools,[11] response surface methods, group technology, exploratory data analysis, and fault-tree analysis.

Formal methods are used for different purposes, but they are all designed to help people understand the behavior of processes, products, mechanisms, and so forth, which otherwise could not be understood as thoroughly. If used properly, the methods and tools are a tremendous aid in design, production, and engineering, yielding sharply reduced life cycle costs, shortened design cycles, and improved quality.

The apparent diversity of the formal methods sometimes masks the more important process that takes place when they are used properly. This underlying process is the scientific approach to problem solving. For a company to be successful using the approach, its employees must develop the habit of identifying problems and solving them so as to improve the company's processes. Once problems are identified and analyzed, the choice of a particular formal method will depend on the situation. Box [Box89] discusses the paramount importance of recognizing that problems represent opportunities to gather information to improve a process. The following paragraphs are provided as a brief introduction to formalized methods.

An SPC standard was developed for the War Department in December 1940 by the American Standards Association. It is a technique for using statistical sampling methods to determine the regularity of a process. The original standard was updated and now the use of SPC is described in a 1985 ANSI standardANSI85.

Design of experiments (experimental design) was invented and developed in England in the 1920s by Fisher. It has been used in agriculture, medicine, and biology. In manufacturing, design of experiments provides tools for designing and conducting experiments in an efficient way so that optimum values for product and process parameters can be identified.

Design-for-assembly software is commercially available to help designers evaluate the benefits of using fewer parts, better fasteners, and more efficient assembly techniques. One product was developed by Boothroyd Dewhurst, Inc. [Dewh85] and has been licensed by approximately 300 companies in the United States and Europe. Many dramatic product improvements have been reported through its use, particularly in the automobile and consumer products industries.

Pugh is a proponent of encouraging creativity during the conceptual design stage and using unbiased evaluation criteria to develop the strongest concepts.

Robust design[12] has come to be associated with Taguchi. His engineering innovations and statistical methods, however, can be addressed separately. He has introduced several new and very important quality engineering ideas. He

11. The tools are histograms, cause-and-effect diagrams, check sheets, Pareto diagrams, graphs, control charts, and scatter diagrams.

12. The terms robust design, robust engineering, and robust product design refer to an engineering philosophy that seeks to reduce variability of some important characteristic of a product in the presence of variability in the manufacturing and use environments. It does not, unless specifically noted, refer to the robustness of an experimental design or of the inferences that can be drawn from an experiment.

stresses the importance of closeness-to-target rather than within-specification objectives. He recommends using statistical design to formulate a product or process that operates on target with smallest variance, is insensitive to environmental disturbances and manufacturing variances, and has the lowest possible cost.[13]

Robust design is achieved through system design, parameter design, and tolerance design. System design is a search for the best available technology, parameter design selects optimum levels for design parameters, and tolerance design establishes the manufacturing tolerances. [Tagu86] Parameter design and tolerance design make use of planned experiments. Although there is general agreement that the principles of robust engineering are an important contribution, the question of the selection of statistical methods for conducting the experiments and analyzing the results remains open within the scientific community.[14] The terms "Taguchi Experiments, "Taguchi Methods, and "Design of Experiments are sometimes used interchangeably by practitioners. We use the term that was applied by the person who performed the experiment.

We did not conduct a survey of which methods are most widely used in the United States. A recent article [Kusa88] from Japan describes the statistical methods mentioned in the presentation to a quality circle conference. The most widely used methods were the Ishikawa tools, design of experiment, and tree analysis (QFD).

One theme that emerged from the discussion of methods and technologies, particularly from the discussion of formal methods, is that there is merit in diversity. Participants were in agreement that no one set of tools can be expected to serve the needs of all users, even within the same company. A consensus emerged that solutions should be problem centered, not tool centered.

4.1 Common Characteristics

We observed several common characteristics in the companies that successfully deployed concurrent engineering:

- Upper management supported the initial change and continued to support its implementation.
- Changes were usually substitutions for previous practices, not just additional procedures.
- The members of the organization perceived a need to change. Usually there was a crisis to be overcome. Often the motivation seemed to center around retaining or regaining market share.
- Companies formed teams for

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13. George E. P. Box, Discussion Section, *Journal of Quality Technology,* Vol. 17, No. 4, (October 1985) p. 189.

14. For an example of such discussions see: Raghu N. Kacker, "Off-Line Quality Control, Parameter Design and the Taguchi Method, *Journal of Quality Technology,* Vol. 17, No. 4, (October 1985), pp. 176-209; Myron Tribus and Geza Szonyi, "The Taguchi Methodology: An Alternative View (December 1987); Romon V. Leon, Anne C. Shoemaker, and Raghu N. Kacker, "Performance Measures Independent of Adjustment: An Explanation and Extension of Taguchi's Signal-to-Noise Ratios, *Technometrics,* Vol. 29, No. 3 (August 1987), pp. 253-285; George Box, "Signal-to-Noise Ratios, Performance Criteria, and Transformations, *Technometrics,* Vol. 30, No. 1 (February 1988), pp. 1-40; Ikuro Kusaba, "Statistical Methods in Japanese Quality Control," *Societàs Quàlitàtis,* Vol. 2, No. 2 (May/June 1988), Union of Japanese Scientists and Engineers; and Genichi Taguchi and Madhav Phadke, "Quality Engineering Through Design Optimization, *Conference Record,* IEEE GLOBECOM 1984 Conference, Atlanta, Georgia, IEEE, pp. 1106-1113.

product development. Teams included representatives with different expertise, such as design, manufacturing, quality assurance, purchasing, marketing, field service, and computer-aided design support.

- Changes included relaxing policies that inhibited design changes and providing greater authority and responsibility to members of design teams. Companies practicing concurrent engineering have become more flexible in product design, in manufacturing, and in support.
- Companies either started or continued an existing program of education for employees at all levels.
- Employees developed an attitude of ownership toward the processes in which they were involved.
- *Companies used pilot projects* to identify problems that were associated with implementing new concurrent engineering techniques and to demonstrate their benefits.
- Companies made a commitment to continued improvement. None of the companies said it was prepared to freeze the latest process as the ultimate solution to design and production.

4.2 Misconceptions

To dispel some misconceptions about concurrent engineering, we list what concurrent engineering *is not*.

First, it is *not* a magic formula for success. The best system cannot compensate for a lack of talent. The companies studied have hired and trained engineers who are able to identify important design parameters, and who are capable of creating solutions to problems. At least one of the companies said that a significant part of their success was the fact that people worked harder. Concurrent engineering is an approach for improving the efficiency of good people who work hard; it provides no guarantees of success.

Second, concurrent engineering is *not* the arbitrary elimination of a phase of the existing, sequential, feed-forward engineering process. For example, it is not the simple, but artificial, elimination of a test-and-fix phase or of full-scale engineering development. Concurrent engineering does not eliminate any engineering function. In concurrent engineering, all downstream processes are co-designed toward a more all-encompassing, cost-effective optimum design.

Third, concurrent engineering is *not* simultaneous or overlapped design and production.[15] Concurrent engineering entails the simultaneous design of the product and of the downstream processes. It does not entail the simultaneous design of the product and the *execution* of the production process, that is, beginning high rate production of an item that has not completed its test, evaluation, and fix phase. On the contrary, concurrent engineering emphasizes completion of all design efforts prior to production initiation.

Winner[16] provides a more

15. At least one spokesperson for manufacturing engineers points out that "design continues throughout a product's life, so that even in high volume production, the design of the production process and the design of the product improvements must be coordinated. Nevertheless, we continue to hold that concurrent engineering does not imply beginning production of a product before its *initial development* has reached a stage where the design has been validated.

16. See [Winn 88] pp. 21-23.

complete list of the misconceptions concerning concurrent engineering that were encountered during the initial study phase.

We intentionally avoided creating a template or checklist that could provide some metric of concurrent engineering. Such an approach would offer a temptation to people who are looking for an easy fix. We did not find a foolproof recipe for success in using concurrent engineering. We believe, however, that companies which focus on on the customer's requirements and priorities, are convinced that quality is the result of improving a process, and hold a philosophy that improvement of the processes of design, production, and support are never-ending responsibilities of the entire enterprise will find themselves practicing something closely related to concurrent engineering.

5. BENEFITS

During the study, we found evidence that application of concurrent engineering methods, as described in the case studies, achieved improved quality, lower cost, and shorter development cycles.

The next three subsections present reported[17] benefits by category: quality, cost, and schedule.

5.1 Quality Improvements

Several of the companies visited during the study reported that their decision to use concurrent engineering procedures can be traced to corporate quality improvement programs. When these companies pursued a vigorous quality program to improve their competitive capabilities, they often found that concurrent engineering was a natural part of such a program.

We observed a trend among U.S. companies toward accepting the view of quality that the Japanese learned from such American pioneers as Sarasohn, Deming, and Juran. Corporations are sending senior executives to Japan and to U.S. quality seminars and courses (that are often based on Japanese extensions to the quality tools originally provided to them by American advisors).

Executives of U.S. companies are learning that improving quality does not have to drive prices up, but that if quality is improved through attention to the system (or process) then costs often go down. The cost savings result from reductions in scrap and rework (the elimination of the so-called "hidden factory"), reduced warranty costs, elimination of inspections, and the resulting improvement in production efficiency. The view of quality as a driver for competitiveness improvements is gaining wider acceptance.

The companies we visited usually associate *quality* of their design with fewer engineering changes as the product enters high volume production and use. They use reduction of scrap and rework as a measure of the quality of their production processes. Some companies that have adopted more strenuous efforts to reduce their process variability use other measures of quality such as Taguchi's loss function.

Examples[18] of reported quality improvements are listed below:

- Aerojet Ordnance salvaged 400,000 pyrotechnic pellets that

17. The data presented by the companies were accepted at face value.

18. A more complete discussion of these cases can be found in Appendix A of [Winn 88].

would have been discarded because of insufficient burn times. The pellets could be used because Aerojet redesigned the loading parameters on the basis of Taguchi experiments. They improved the consistency of tracer rounds as measured by μ/σ (mean/standard deviation) by a factor of 5. Their support on one munitions program was instrumental in identifying correct design parameter values so that yield was improved from approximately 20 percent to 100 percent, a 400 percent improvement.

- AT&T achieved a fourfold reduction in variability in a polysilicon deposition process for very large scale integrated (VLSI) circuits (1.75 micron design rules) and achieved nearly two orders of magnitude reduction in surface defects by using Taguchi methods.
- AT&T reduced defects in the 5ESS™ programmed digital switch up to 87 percent through a coordinated quality improvement program that included product and process redesign.
- Deere reduced the number of inspectors by two thirds by emphasizing process control and by linking design and manufacturing processes.

Other reported quality improvements associated with the use of concurrent engineering are described by Winner[19].

5.2 Cost Reductions

Reports of cost reduction include the following classes of cost savings:

- Reduced bid in company proposals.

McDonnell Douglas had a 60 percent reduction in life-cycle cost and 40 percent reduction in production cost on a short range missile proposal. Boeing reduced bid on mobile missile launcher and is realizing costs 30 to 40 percent below bid.

- Reduced costs in the design phase.

AT&T and IBM reduced the number of design iterations and made extensive use of computer-aided design verification during design saving money and time. Deere reduced product development cost 30 percent.

- Reduced costs during fabrication, manufacture, and assembly.

IBM reduced direct labor costs in system assembly by 50 percent. ITT saved 25 percent in ferrite core bonding production costs. Allied Signal saved more than $3,000,000 annually in a bulk chemical process as a result of experimental design.

- Costs reduced by parts reduction and inventory control.

Boeing reduced parts lead time by 30 percent. AT&T reduced parts by one third on surface mount technology (SMT) packs and reduced costs to one ninth. AT&T Denver Works decreased in-process inventory 64 percent. Deere reduced the number of parts to fabricated and stocked by 60 to 70 percent. Hewlett-Packard Instruments

™ 5ESS is a trademark of AT&T

19. See [Winn 88] pp. 23-26.

Division recognized inventory reductions of 62 percent and a productivity increase of 250 percent.

- Costs reduced by reducing scrap and rework.

  Deere reduced scrap and rework costs by 60 percent. Using a Taguchi experiment, ITT saved $400,000 by reducing rejects on one product. ITT saved $1,100,000 annually by improving a soldering process based on a Taguchi experiment.

5.3 Decreased Development Time

There were many reports of shortened development cycles. Experienced engineers pointed out that even significantly improved methods will not eliminate all the bottlenecks and long lead-time items found in some large, complex products such as weapons systems. Nevertheless, the reported savings indicate that substantial improvements were achieved. Samples are listed below:

- AT&T reduced the total process time for the 5ESS Programmed Digital Switch by 46 percent in 3 years.
- Deere reduced product development time for construction equipment by 60 percent.
- ITT reduced the design cycle for an electronic countermeasures system by 33 percent, and its transition-to-production time by 22 percent. Time to produce a certain cable harness was reduced by 10 percent.

Winner[20] presents additional reports of reduced development times associated with the use of concurrent engineering.

5.4 Interactions

We found it useful to classify the methods and tools associated with concurrent engineering into three categories and to describe payoffs in terms of quality, cost, and schedule improvements. These classifications are not intended to imply independence. In fact, interactions among the approaches are common. We found that companies typically employ some combination of approaches and they experience some mix of benefits. Some of these interactions are discussed below.

- *Multifunction teams.* The proximity and interaction of personnel from the different disciplines have a major positive effect by itself. Assignment of decision responsibility to the team allows big improvement in problem resolution which improves product and process development times.
- *Systems engineering.* Analysis of design features and their relation to observed reliability and producibility is a prerequisite to cross training personnel so that they achieve a systems perspective. The analyses and training are essential to quantitative predictions of producibility and reliability. Computer support has proven useful in performing these analyses without delaying the design process.
- *Computer support.* A parts database is valuable in conceptual design in terms of evaluating options. Product definition and shared common product design databases are enabling forces for a variety of concurrent engineering functions. Feasibility

20. See [Winn 88] p. 27.

analysis, simulations, integration management, design release, and transfer to automated production processes all support decision making throughout the engineering process.

- *Complexity management.* The level of program integration and complexity affects the leverage of concurrent engineering methods and techniques. For complex systems, systems integration must address both management and design systems. Product and process simulations are important at the systems level. At the component level, process and product optimization to achieve robust design may be of more immediate value.
- *Integration.* At the component level, concurrent engineering can be implemented by integrating the design system with a flexible manufacturing cell because the design and manufacturing systems employ features with known variability. This integration ensures that cost, performance, and quality objectives are met.

6. PITFALLS

The benefits cited in this report are encouraging, but they have not been achieved easily. One employee who is familiar with the success story of one of the companies encountered in this study related some of the mistakes and lessons learned in their implementation of concurrent engineering.

" . . . really impressive savings (hundreds of millions of dollars) remain largely unrecognized because they result only from improvements of the larger 'systems' over which only top management has control. These larger systems include policies of the company; training that people receive; actions of management; policies for purchasing parts; barriers between departments, between divisions, etc.; emphasis on short-term thinking and profits; policies for never-ending improvement; the way employees are evaluated; fostering of teamwork; and so forth. To date, most top managers have failed to comprehend, or at least execute, their critical responsibility. Their verbal 'support' is simply not sufficient.

He continues:

Our corporation's lack of leadership for concurrent engineering has resulted in an effort without any clear direction or guidance both within many divisions and between the divisions. This fosters the widespread perception that concurrent engineering is a fad that will eventually go away . . . .

"Most divisions placed too much emphasis on the techniques of concurrent engineering (SPC, QFD, Design of Experiments, etc.) and not enough emphasis on the critical management philosophy underlying the application of the techniques. This partly explains the lack of top management understanding and involvement. Top management views concurrent engineering as something the lower levels learn and apply . . . .

Sometimes the customer's acquisition strategy is a barrier. In one case, the customer elected to serve as system integrator and to have the program office control communication between the engineering and manufacturing groups. The contract required the engineering and manufacturing branches of the company to maintain separate relationships with the program office. For example, when the engineering branch is funded to design improvements or modifications for the weapon system, the output of this activity is an engineering change proposal (ECP) that constitutes a full technical change of the technical data package. Depending on the nature and scope of the ECP, the resulting manufacturing is accomplished by the same company or else by another vendor. Final assembly is accomplished by the manufacturing division of the first company.

This contracting method separates engineering from manufacturing and, when coupled with a fixed price production contract, has several disadvantages for concurrent engineering. First, to reduce cost, improve quality, and reduce scrap, the company is limited to production process changes. Engineering changes can only be made if significant cost reductions can be demonstrated, at which time a value engineering change proposal (VECP) is processed by the engineering branch and submitted to the program manager for approval. The result is that engineering changes in production are limited to recurring cost reduction items where the cost savings outweigh the implementation costs on a three-year payback. Second, some engineering changes are designed by competing engineering houses, so that the production organization and processes are unknown to the designers. Thus, continuous improvement is stifled and production is decoupled from design. In this case, the program office, while intending to serve as an integrator, was actually a barrier between different divisions of the same company.

A third problem is the expectation of instant success—an immediate reduction in costs with no investment. Because more people participate in earlier stages of design, the initial expenses of a development project may increase. Several companies report that concurrent engineering extends the early design effort so the early design functions may take more time and cost more. This experience was not shared by all practitioners. Even where encountered, its effect was compensated by the savings when the initial production was started. In each reported case, concurrent engineering resulted in a shorter overall development cycle.

6.1 Issues

Members of the working groups raised several issues about concurrent engineering. Some[21] of the issues are listed below:

Avoid overregulation. Assuming that concurrent engineering is a good philosophy for product development, how can DoD encourage its use without imposing a particular solution? Senior DoD executives can, by including discussions of total quality management and concurrent engineering as part of their continuing dialogue with industry executives, show their interest and support for improving the development process. Beyond demonstrating an interest, a statement of DoD policy on concurrent engineering, without being overly restrictive, is needed.

Simplify the acquisition process while encouraging use of concurrent engineering. Both industry and government participants expressed a belief that creation of additional new programs or publication of more regulations without eliminating or modifying current practices is not the best way to improve the acquisition process. They expressed a strong preference for consolidation, simplification, and coordination of existing standards and regulations, including updating the "templates to include concurrent

21. For a more extensive list of issues see [Winn 88] pp. 33-35, 46-48, 110, and 125.

engineering methods.

Improve the customer-supplier relationships in the DoD acquisition process. This issue remains open. The benefits of establishing closer relationships with suppliers are well known among followers of Deming and practitioners of just-in-time manufacturing. At the same time, the benefits of competition cannot be overlooked and support for competitive policies is very strong in the Congress.

Can DoD managers evaluate a company's claims about concurrent engineering without imposing a solution? Workshop participants from the defense industrial base expressed concern about their company's continued ability to compete for DoD contracts. They are ready to make the changes that they believe are needed to become more competitive, but they do not want to start an internal improvement program, only to find that DoD will later impose some slightly different program. Neither did they want to implement some improvement whose benefits will not be understood by proposal evaluators.

7. PRINCIPAL FINDINGS

The study team reached the ten findings listed below.

7.1 Concurrent Engineering Works.

The methods and techniques of concurrent engineering have been used to raise the quality, lower the cost, decrease the deployment time, and increase the adherence to desired functionality of a variety of products.

Concurrent engineering has been used for applications that range from simple components to complex systems. The success of concurrent engineering over this variety of applications as well as the study team's understanding of how and why concurrent engineering works leads to the second finding.

7.2 Concurrent Engineering Has Worked for DoD.

Concurrent engineering has been used in the DoD acquisition process and its use was reported to have helped provide weapons systems in less time, at lower cost, and with higher quality.

Concurrent engineering methods are being used in weapons system projects at demonstration/validation, full-scale de- velopment, and in production. Nine[22] of the companies contacted during this study provided information that they are using concurrent engineering on weapons system programs. They are convinced that further progress toward a fuller implementation of concurrent engineering is possible, not only in their companies, but throughout the DoD contracting environment.

7.3 Adopting Concurrent Engineering Will Not Be Easy.

There are systemic and individual inhibitors to the use of concurrent engineering in weapons system acquisitions.

The inhibitors to using concurrent engineering are found in the contractors' organizations and practices as well as in DoD's practices and policies. Capital investment decisions,[23] poor horizontal communication, local optimizations, and

22. The companies involved in weapons system development and production were Aerojet Ordnance, Bell Helicopter, Boeing Aircraft (Ballistic Systems Division), General Dynamics, Grumman Aircraft, McDonnell Douglas, Northrop, ITT Avionics, and Texas Instruments.

23. Robert H. Hayes, Steven C. Wheelwright, and Kim B. Clark, *Dynamic Manufacturing*, The Free Press, New York (1988), pp. 61-90.

misunderstanding of the importance of quality are some of the barriers that must be overcome by contractors. Unrealistic cost and schedule constraints, excessive reliance on specifications and standards, and contract language that assumes an adversarial relationship between the customer and the developer are examples of government barriers to using concurrent engineering.[24]

7.4 There Is an Opportunity for Change.

The circumstances are right for DoD to encourage the further deployment of concurrent engineering in weapons system acquisitions.

This follows from an observation that commercial industry and, to some extent, defense industry have already begun to demonstrate success using concurrent engineering. Basic methods of concurrent engineering exist and are in use and technological support exists. Also, the need for developing weapons systems in less time at lower cost and with the assurance that they will operate satisfactorily when they are fielded is heightened by budget realities.

7.5 Avoid Past Mistakes.

Industry experts believe that if concurrent engineering becomes a slogan or a new area of specialization instead of a systematic approach applied across engineering disciplines, then the deployment effort will be counterproductive.

A broad vision is needed, one which can lead to continuous, sustained improvement in the engineering processes applied to all DoD weapons systems.

24. For further discussion of barriers see *Industrial Insights on the DoD Concurrent Engineering Program*, The Pymatuning Group, Inc. (October 1988).

7.6 Continue Research and Development.

Continued effort is needed to develop the methods and technology necessary for advances in concurrent engineering.

The need for continued improvement in solid modeling, process-planning techniques and computer support, finite element modelling, simulation, integration of computer-based tools, and standardization of product description semantics was stated at many of the sites visited. The Computer-aided Acquisition Logistic Support (CALS) initiative has encouraged cooperative efforts by industry to develop unified databases and integrated design tools, but the results are not yet ready for deployment in an open market. Many companies are capturing lessons learned in the rule and knowledge bases that support their design environments.

7.7 Help Is Needed.

Several companies reported that funding for IR&D projects intended to provide an infrastructure for concurrent engineering is no longer available.

Companies that implemented elements of concurrent engineering did so either because they were faced with a crisis or else they were companies with a tradition of continuous improvement for whom concurrent engineering is another stage in the process. For companies in the first category, the crisis provided motivation, but changing the way people worked was a challenging task. Companies in the second group have established programs for encouraging people to re-examine their work continually to find improvements.

7.8 Top-level Support Is Essential.

Implementation of concurrent engineering requires top-down commitment across different company functions.

Because several years may pass before company-wide benefits are apparent, senior management support is essential to prevent premature termination of new business approaches. Early success with pilot projects helps promote acceptance of new methods and top-down support may be needed to ensure that pilot projects are carefully selected and adequately supported.

In each case described to us, a company implemented changes by first trying new methods on pilot projects. The pilot projects serve to identify elements of a new plan that need improvement and they demonstrate benefits of using new techniques. They also served to develop the initial cadre of corporate members skilled in the new methods. This observation is consistent with published reports of key elements for effecting change.

7.9 Pilot Projects Can Be Helpful.

Pilot projects have been useful in demonstrating the benefits of concurrent engineering.

With respect to technology, the study team considered whether there were domains that should be avoided.

7.10 Concurrent Engineering Is a Robust Approach.

In this study, concurrent engineering was found to be useful in a range of applications that differed in terms of the maturity and type of technology used in the product and the production process.

There are some methods, for example, that are particularly well suited to applications where the technology is poorly understood or hard to control. An example of this is the application of design of experiments to the design and production of traveling wave tubes at ITT.

8. RECOMMENDATIONS

The IDA report [Winn88] contained seven recommendations for the Department of Defense.

- **Recommendation 1**

That the Secretary of Defense and OSD's principal acquisition managers act to encourage the use of concurrent engineering in weapons system acquisitions.

- **Recommendation 2**

That DoD principal acquisition managers establish a policy to use concurrent engineering as an implementation mechanism for total quality management.

- **Recommendation 3**

That the Office of the Secretary of Defense (OSD) should encourage the establishment of pilot programs whose objectives are to demonstrate that concurrent engineering, when deployed in defense industries and applied to DoD procurements, has the potential to yield higher quality products at a lower cost and in a shorter period of time.

- **Recommendation 4**

That OSD, in encouraging the implementation of concurrent engineering, build upon the beneficial aspects of existing DoD, national, state, and private manufacturing improvement initiatives.

- **Recommendation 5**

That DoD implement an education and training effort that starts with the *senior OSD acquisition managers and then progresses to the lower levels through the acquisition chain.* Once started at the top, lower levels can be trained concurrently.

- **Recommendation 6**

That DoD encourage industry to develop and improve the methods and technologies specifically required to support the use of concurrent engineering in weapons system acquisition programs.

- **Recommendation 7**

That OSD acquisition managers should initiate a process to identify and analyze statutes, rules, regulations, directives, acquisition procedures, and management practices that act as barriers or inhibitors to the adoption and use of concurrent engineering.

9. FUTURE RESEARCH

At one of the workshops, participants were asked to identify critical research topics to support concurrent engineering. Their response showed the need for a framework that could relate the goals, functions, and capabilities that must be in place for concurrent engineering to succeed. Such a framework was developed and is described[25] in the IDA report. It describes the technical building blocks that provide the capabilities which support the critical functions necessary to achieve the goals of improving quality while simultaneously reducing cost and schedule.

The building blocks are labeled as data, information frameworks, tools and models, manufacturing processes, and design processes. Each category is described below.

The first area, *data*, includes the kinds of information that needs to be brought to the design process for concurrent engineering. There is a requirement for a common information architecture so that information users (e.g., designers) and information suppliers (e.g., maintenance organizations) can have a common understanding of the meaning of the information.

The second group, *information frameworks*, consists of a structure of specifications and standards for establishing, storing, executing, and evolving information-based policies and tools. An information framework also has capabilities to organize, access, and evolve the data used by the policies and tools. Using a conventional or standardized framework that has been designed for evolvability and tailorability allows for easier interaction among tools, among engineers, among teams, and among organizations. DoD has several information framework efforts underway. These include systems driven by the needs of airframe specialists, electronics specialists, logisticians, and software engineers. It is important that DoD integrate the vision of these efforts.

The third area, *tools and models*, deals with improving the tools directly required to support the engineer. The report discusses a broad array of empirical, simulation, and analytical models. These include process models, assembly and cost models, and manufacturing system models.

The fourth, *manufacturing processes*, addresses improvement efforts in integration of the design systems in manufacturing cells and systematic techniques for acquiring and analyzing data that describe the capabilities and capacities of the manufacturing systems. This

25. See Appendix C of [Winn 88].

includes matters related to flexible manufacturing cells, production process technologies, and design of experiments and other statistical methods.

The last category, *design processes*, includes work that needs to be done to improve understanding of the design process itself. This concerns the process of design synthesis by the individual and group and the psychological and sociological phenomena in the execution of a team design process.

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